

# Digital Low-Pass Filter Implementation #1

Define sampling frequency

$$F_s := 44100$$

Define cutoff frequency

$$F_c := 14000$$

Normalized cutoff frequency

$$f_c := 2 \cdot \frac{F_c}{F_s}$$

$$f_c = 0.635$$

Define Filter Q

$$q := 10$$

$$Q := \frac{1}{q}$$

Define Filter Parameters

$$F := 2 \cdot \sin\left(f_c \cdot \frac{\pi}{2}\right)$$

$$F = 1.68$$

$$A := \frac{F^2}{2}$$

$$A = 1.411$$

$$B := A$$

Define Transfer Function (1st column is numerator coefficients in transfer function and 2nd column is denominator coefficients in transfer function). So this filter is a 2nd order IIR.

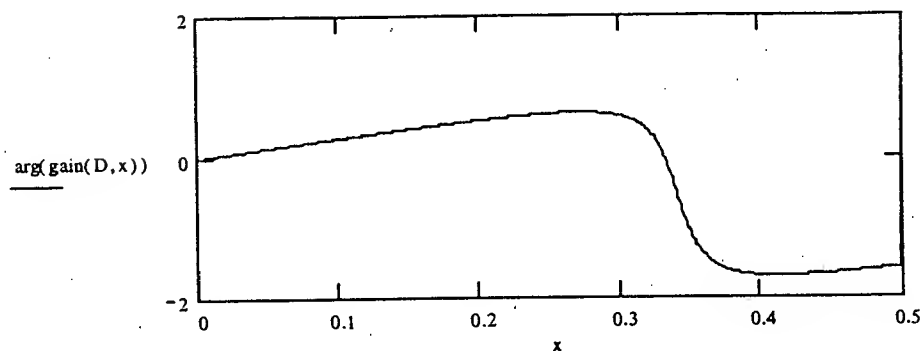
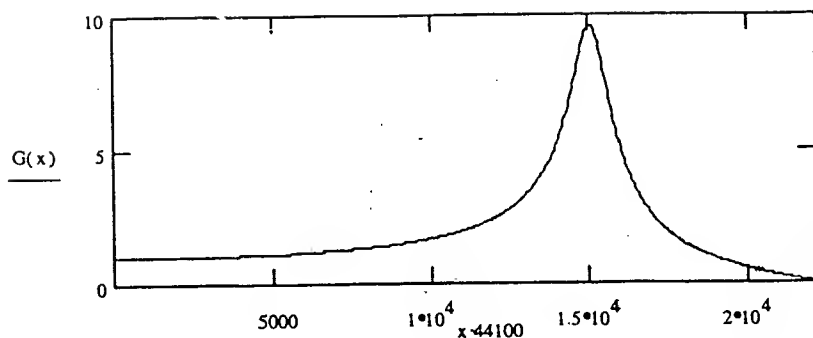
$$D := \begin{bmatrix} B & 1 \\ B - (2 - F \cdot Q - F^2) & \\ 0 & (1 - F \cdot Q) \end{bmatrix}$$

$$D = \begin{bmatrix} 1.411 & 1 \\ 1.411 & 0.991 \\ 0 & 0.832 \end{bmatrix}$$

Plot frequency and phase response of the filter

$$x := 0, .001, .5$$

$$G(x) := | \text{gain}(D, x) |$$



# Digital HI-Pass Filter #1

Define sampling frequency

$$F_s := 44100$$

Define cutoff frequency

$$F_c := 2000$$

Normalized cutoff frequency

$$f_c := 2 \cdot \frac{F_c}{F_s}$$

Define Filter Q

$$q := 2$$

$$Q := \frac{1}{q}$$

Define Filter Parameters

$$F := 2 \cdot \sin\left(f_c \cdot \frac{\pi}{2}\right)$$

$$F = 0.284$$

$$A := \frac{F^2}{2}$$

$$A = 0.04$$

$$B := A$$

Define Transfer Function (1st column is numerator coefficients in transfer function and 2nd column is denominator coefficients in transfer function). So this filter is a 2nd order IIR.

$$D := \begin{bmatrix} 1 & 1 \\ -2 & -(2 - F \cdot Q - F^2) \\ 1 & (1 - F \cdot Q) \end{bmatrix}$$

$$D = \begin{bmatrix} 1 & 1 \\ -2 & -1.777 \\ 1 & 0.858 \end{bmatrix}$$

Calculate gain compensation

$$PK := \frac{4}{(4 - 2 \cdot F \cdot Q - F^2)}$$

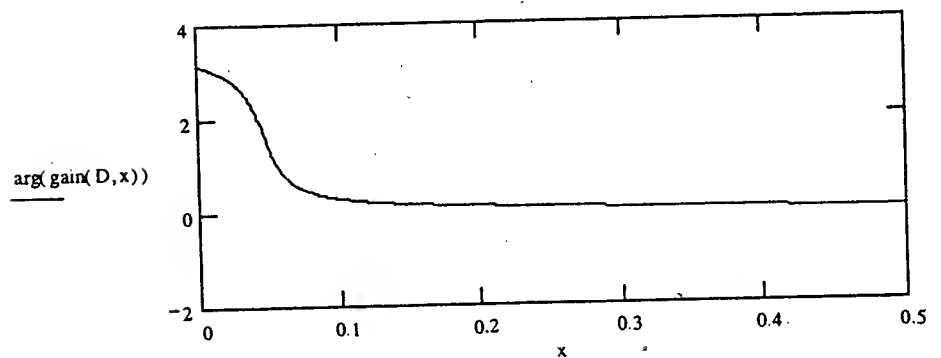
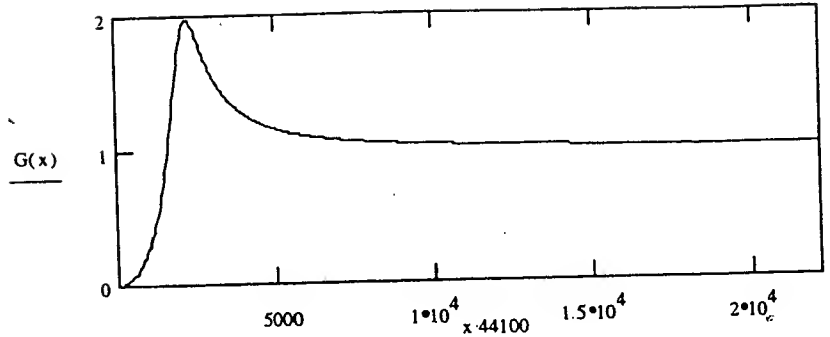
$$K := \frac{1}{PK}$$

$$K = 0.909$$

Plot frequency and phase response of the filter

$$x := 0, .001, .5$$

$$G(x) := K \cdot |\text{gain}(D, x)|$$



# Digital Low-Pass Filter Implementation #2 (one-zero)

Define sampling frequency

$$F_s := 44100$$

Define cutoff frequency

$$F_c := 2000$$

Normalized cutoff frequency

$$f_c := 2 \cdot \frac{F_c}{F_s}$$

$$f_c = 0.091$$

Define Filter Q

$$q := 10$$

$$Q := \frac{1}{q}$$

Define Filter Parameters

$$F := 2 \cdot \sin\left(f_c \cdot \frac{\pi}{2}\right)$$

$$F = 0.284$$

$$A := \frac{F^2}{2}$$

$$A = 0.04$$

$$B := A$$

Define Transfer Function (1st column is numerator coefficients in transfer function and 2nd column is denominator coefficients in transfer function). So this filter is a 2nd order IIR.

$$D := \begin{bmatrix} 0 & 1 \\ B & -(2 - F \cdot Q - F^2) \\ 0 & (1 - F \cdot Q) \end{bmatrix}$$

$$D = \begin{bmatrix} 0 & 1 \\ 0.04 & -1.891 \\ 0 & 0.972 \end{bmatrix}$$

Plot frequency and phase response of the filter

$$x := 0, .001 \dots .5$$

$$G(x) := | \text{gain}(D, x) |$$

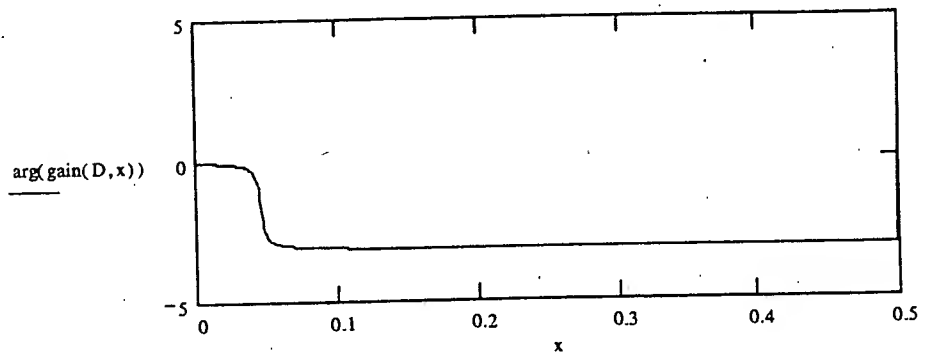
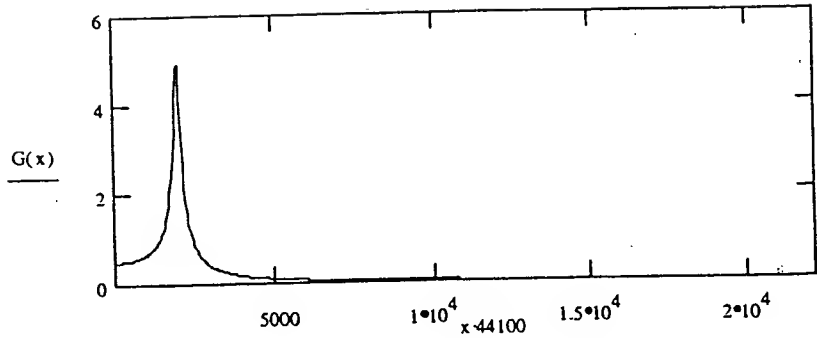


FIG. A3

# Digital Shelving EQ section based on an All-pass filter section

Define sampling frequency

$$F_s := 44100$$

Define critical frequency

$$F_c := 10000$$

Normalized critical frequency

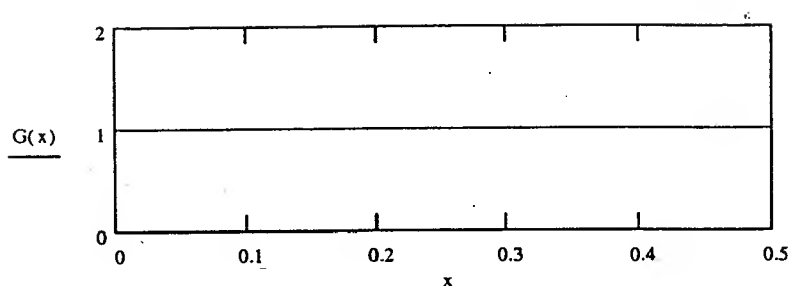
$$\omega_c := 2 \cdot \pi \cdot \frac{F_c}{F_s}$$

Define gain/cut

$$k := 4$$

Define Filter parameters

$$\gamma := \frac{\left( \tan\left(\frac{\omega_c}{2}\right) - 1 \right)}{\left( \tan\left(\frac{\omega_c}{2}\right) + 1 \right)}$$



Define Transfer Function (1st column is numerator coefficients in transfer function and 2nd column is denominator coefficients in transfer function). So this filter is a 1st order IIR.

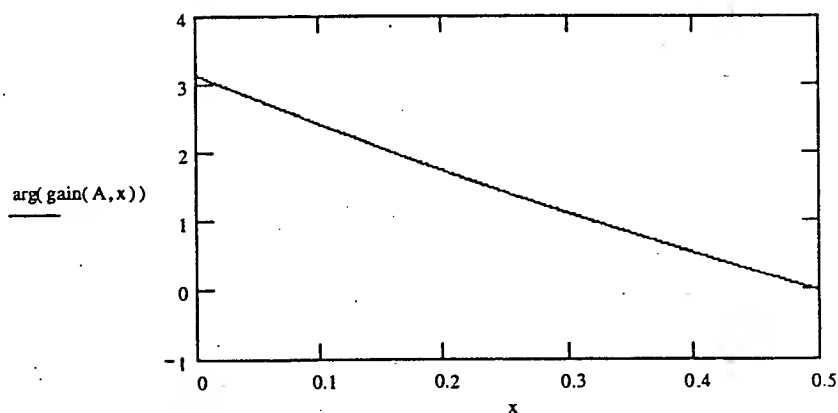
$$A := \begin{bmatrix} -\gamma & 1 \\ -1 & \gamma \end{bmatrix}$$

$$A = \begin{bmatrix} 0.073 & 1 \\ -1 & -0.073 \end{bmatrix}$$

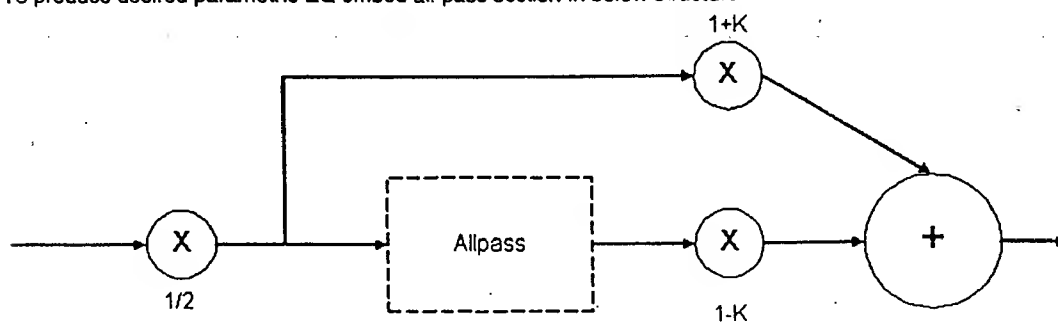
Plot frequency and phase response of the filter

$$x := 0, .001, 0.5$$

$$G(x) := | \text{gain}(A, x) |$$



To produce desired parametric EQ embed all-pass section in below structure



In a DSP implementation, the filter output is computed as per the above signal flow. Below we calculate the overall transfer function of the above system by transforming the numerator of the all-pass section as necessary.

0005

FIG. A4 (Sheet 1 of 2)

$D := A$

$G := D^{<1>}$       extract denominator

$F := D^{<0>}$       extract numerator

$$M := \frac{(1-k)}{2}$$

$$L := \frac{(1+k)}{2}$$

build new numerator:

$$F_0 := M \cdot F_0 + L$$

$$F_1 := M \cdot F_1 + L \cdot G_1$$

$$D^{<0>} := F$$

$$D = \begin{bmatrix} 2.39 & 1 \\ 1.317 & -0.073 \end{bmatrix}$$

Plot magnitude response:

$| \text{gain}(D, x) |$

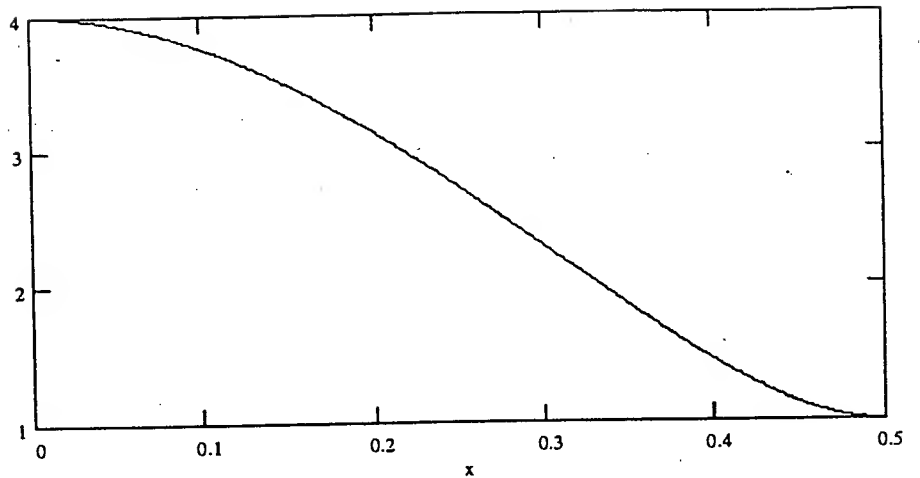


FIG. A4 (Sheet 2 of 2)

0006

# Digital Notch/Parametric EQ section based on an all-pass section

Define sampling frequency

$F_s := 44100$

Define critical frequency

$F_c := 5500$

Normalized critical frequency

$\omega_c := 2 \cdot \pi \cdot \frac{F_c}{F_s}$

Define Filter Q

$Q := 4$

Define gain/cut

$k := 4$

Define Filter parameters

$\gamma := -\cos(\omega_c)$

$\text{fbeta} := \frac{\omega_c}{2 \cdot Q}$

$\text{fbeta} := \text{if} \left( \text{fbeta} > \frac{\pi}{4}, \frac{\pi}{4}, \text{fbeta} \right)$

$\beta := \frac{1 - \tan(\text{fbeta})}{1 + \tan(\text{fbeta})}$

Define Transfer Function (1st column is numerator c and 2nd column is denominator coefficients in trans order IIR.

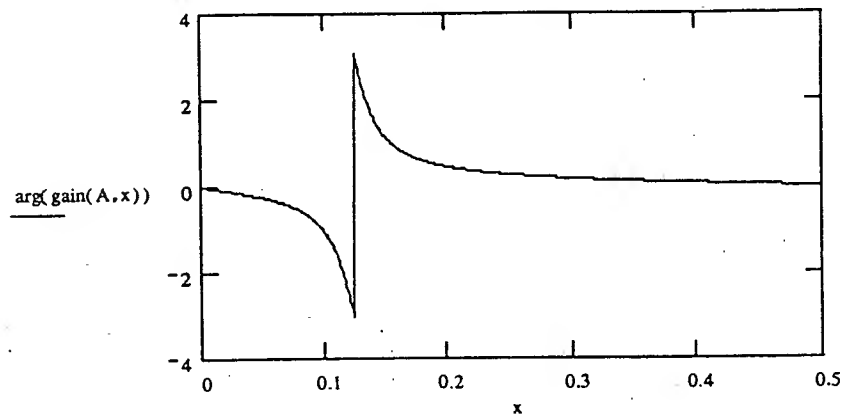
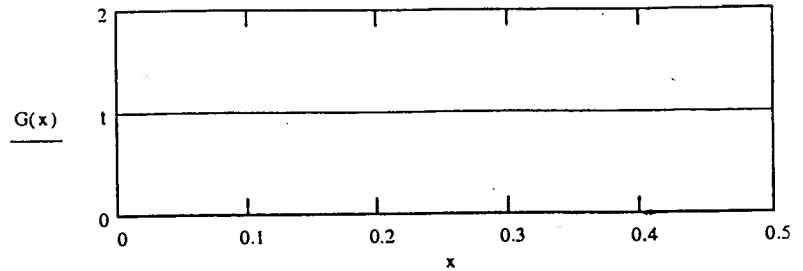
$A := \begin{bmatrix} \beta & 1 \\ \gamma \cdot (1 + \beta) & \gamma \cdot (1 + \beta) \\ 1 & \beta \end{bmatrix}$

$A = \begin{bmatrix} 0.821 & 1 \\ -1.29 & -1.29 \\ 1 & 0.821 \end{bmatrix}$

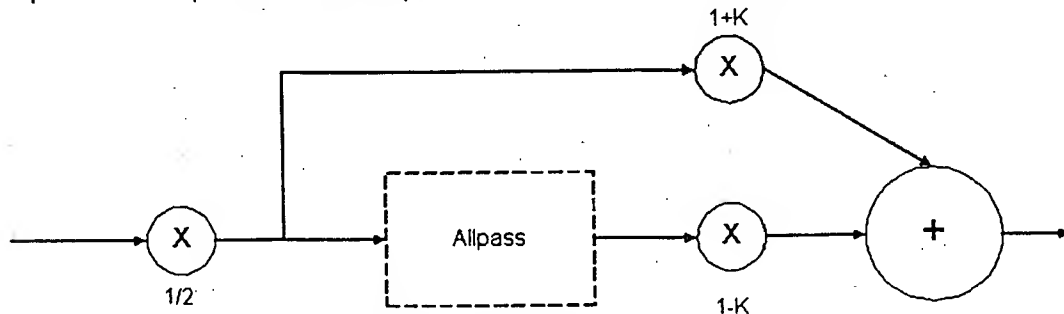
Plot frequency and phase response of the filter

$x := 0, .001, 0.5$

$G(x) := | \text{gain}(A, x) |$



To produce desired parametric EQ the all-pass section is embedded in the below structure:



In a DSP implementation, the filter output is computed as per the above signal flow. Below we calculate the overall transfer function of the above system by

transforming the numerator of the all-pass section as necessary.

$D := A$

$G := D^{<1>}$

extract denominator

$F := D^{<0>}$

extract numerator

$$M := \frac{(1-k)}{2}$$

$$L := \frac{(1+k)}{2}$$

build new numerator:

$$F_0 := M \cdot F_0 + L$$

$$F_1 := M \cdot F_1 + L \cdot G_1$$

$$F_2 := M \cdot F_2 + L \cdot G_2$$

$$D^{<0>} := F$$

$$D = \begin{bmatrix} 1.268 & 1 \\ -1.29 & -1.29 \\ 0.553 & 0.821 \end{bmatrix}$$

Magnitude Response:

$| \text{gain}(D, x) |$

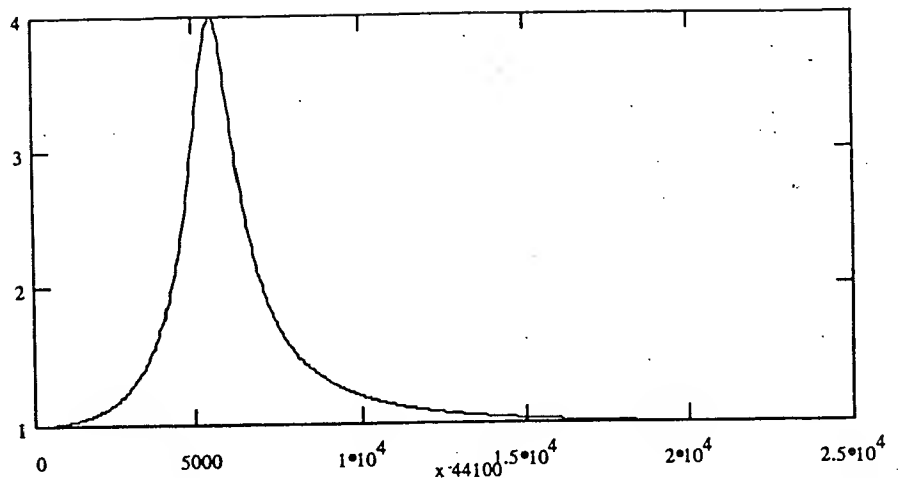


FIG. A5 (Sheet 2 of 2)

### Digital Implementation of a Weighted Notch #1

Consists of 3 parametric EQ section designed using the procedure described in "Notch/Parametric EQ section based on an all-pass section"

2 low Q gain section surround the critical frequency notch.

For compensation section #1 and #2 (D1 and D2 respectively) Q is 2 and k is 1.5 resulting in the below transfer functions. The resulting filters are two 2nd order IIR filters where column 0 represents the numerator and column 1 represents the denominator.

$$D1 := \begin{bmatrix} 1.076 & 1 \\ -1.283 & -1.283 \\ 0.619 & 0.695 \end{bmatrix}$$

$$D2 := \begin{bmatrix} 1.089 & 1 \\ -1.079 & -1.079 \\ 0.554 & 0.643 \end{bmatrix}$$

For critical frequency section #3 (D3 below) Q is 10 and k is 0. The resulting filter is a 2nd order IIR filters where column 0 represents the numerator and column 1 represents the denominator.

$$D3 := \begin{bmatrix} 0.962 & 1 \\ -1.363 & -1.363 \\ 0.962 & 0.925 \end{bmatrix}$$

Plot of the overall frequency response of the 3 IIR filters cascaded

$x := 0, .001.. 0.5$

$G1(x) := \text{gain}(D1, x)$

$G2(x) := \text{gain}(D2, x)$

$G3(x) := \text{gain}(D3, x)$

$H(x) := 20 \cdot \log(G1(x) \cdot G2(x) \cdot G3(x))$

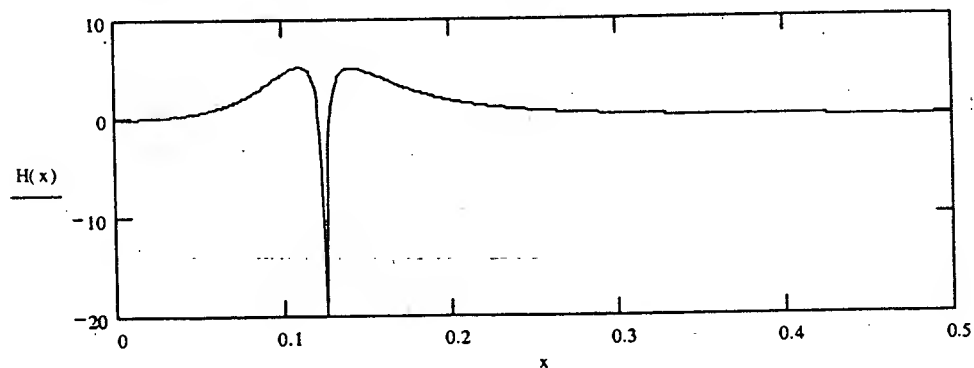


FIG. A6



## Digital Implementation of a Weighted Notch #2

Consists of 3 parametric EQ section designed using the procedure described in  
 "Notch/Parametric EQ section based on an all-pass section"

One medium Q gain compensation section centered around two notches.

For compensation section #1 (D1 below) Q is 4 and k is 4 resulting in the below transfer function. The resulting filters is a 2nd order IIR filters where column 0 represents the numerator and column 1 represents the denominator.

$$D1 := \begin{bmatrix} 1.268 & 1 \\ -1.29 & -1.29 \\ 0.553 & 0.821 \end{bmatrix}$$

For critical frequency notches sections #2 and #3 (D2 and D3 below respectively) Q is 10 and k is 0. The resulting filters are two 2nd order IIR filters where column 0 represents the numerator and column 1 represents the denominator.

$$D2 := \begin{bmatrix} 0.963 & 1 \\ -1.383 & -1.383 \\ 0.963 & 0.926 \end{bmatrix}$$

$$D3 := \begin{bmatrix} 0.962 & 1 \\ -1.343 & -1.343 \\ 0.962 & 0.923 \end{bmatrix}$$

Plot of the overall frequency response of the 3 IIR filters cascaded:

$x := 0, .0001, 0.5$

$G1(x) := | \text{gain}(D1, x) |$

$G2(x) := | \text{gain}(D2, x) |$

$G3(x) := | \text{gain}(D3, x) |$

$H(x) := 20 \cdot \log(G1(x) \cdot G2(x) \cdot G3(x))$  (cascaded response)

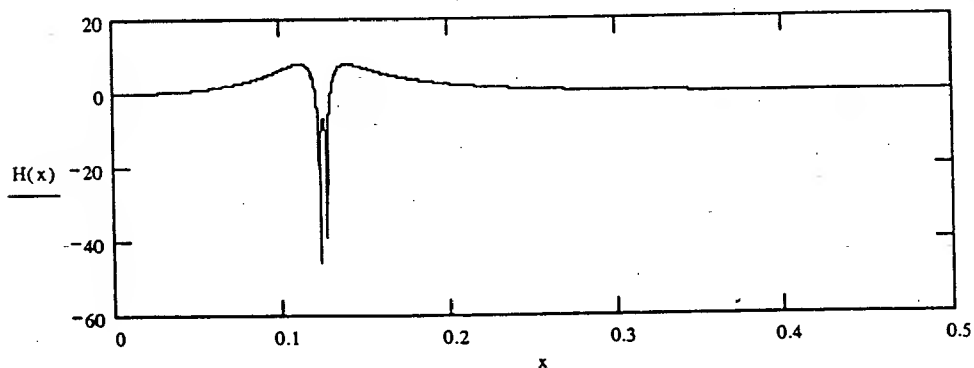
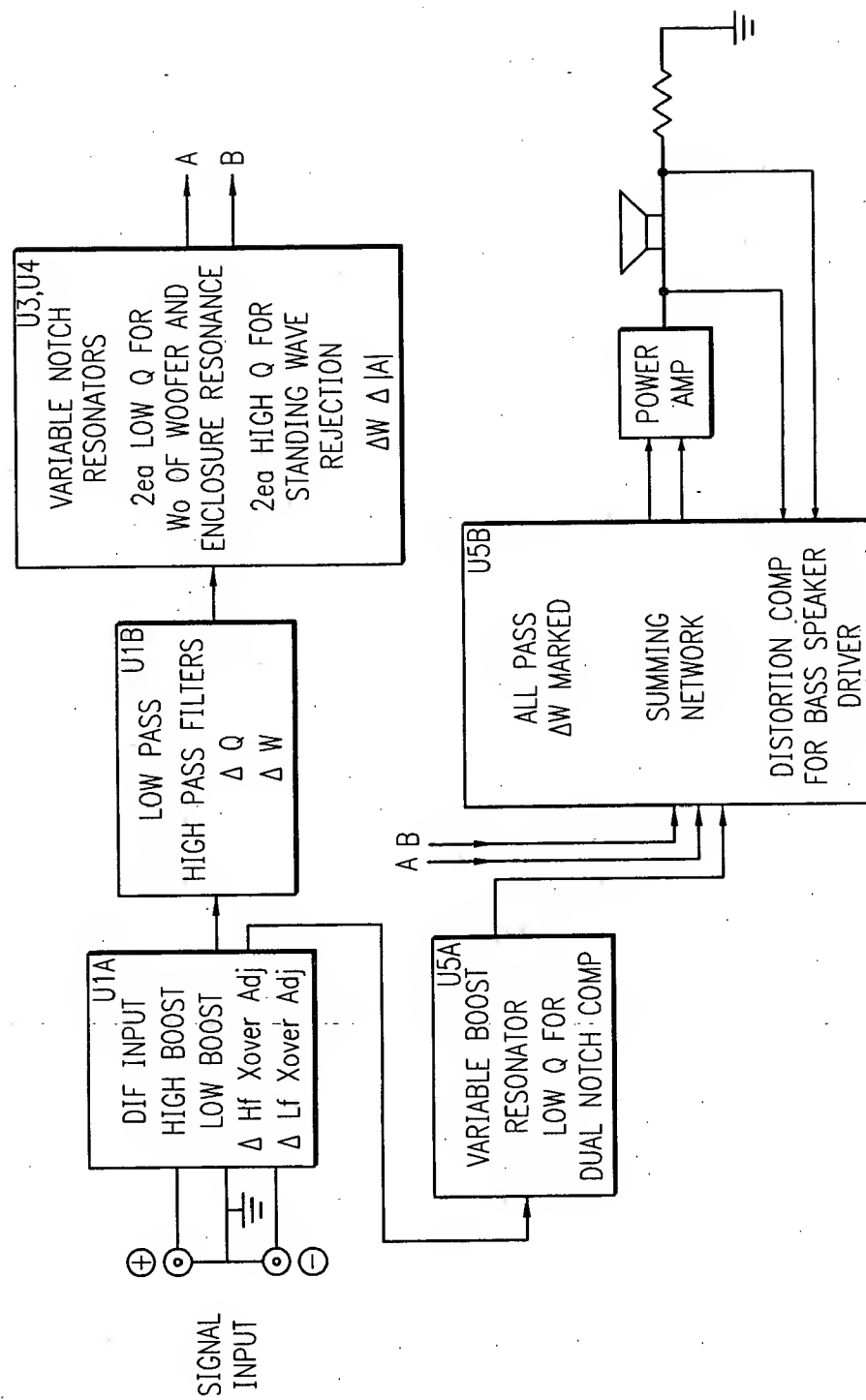


FIG. A7

0010



# SLOPE EQ AND BANDPASS FILTER ADJUSTED

$W_L = 65\text{Hz}$ ,  $44\text{Hz}$  (PARALLEL CAPS)

$W_H = 17\text{kHz}$

$W_{LX} = 400\text{Hz} \rightarrow 20\text{Hz}$

$W_{HX} = 3\text{kHz} \rightarrow 25\text{kHz}$

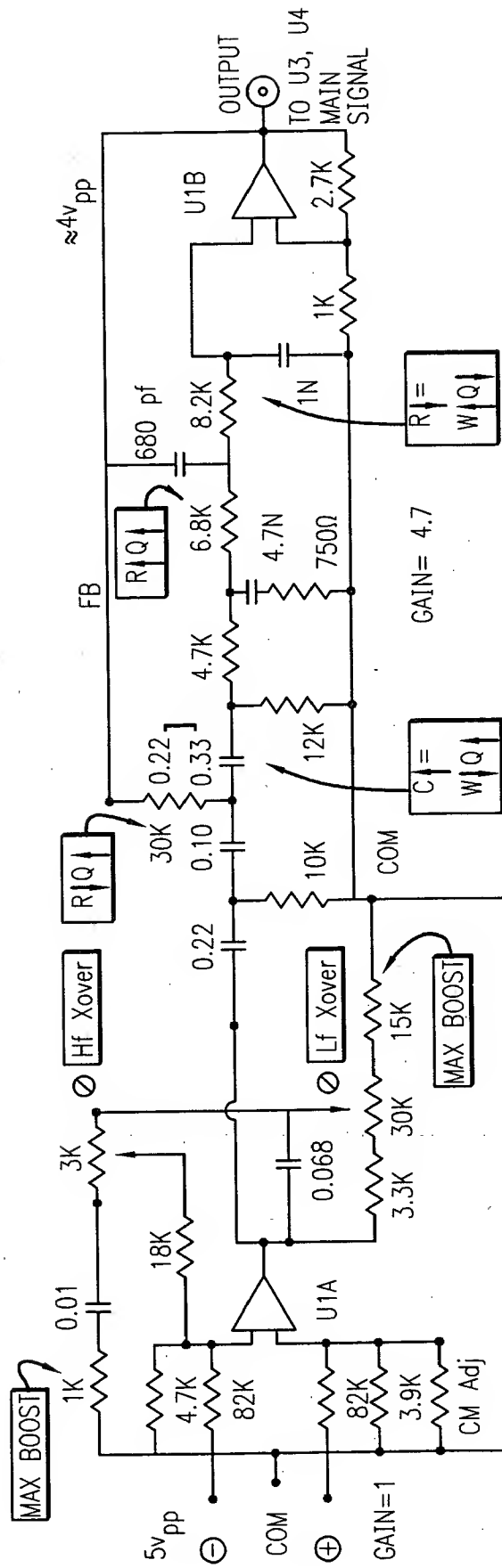
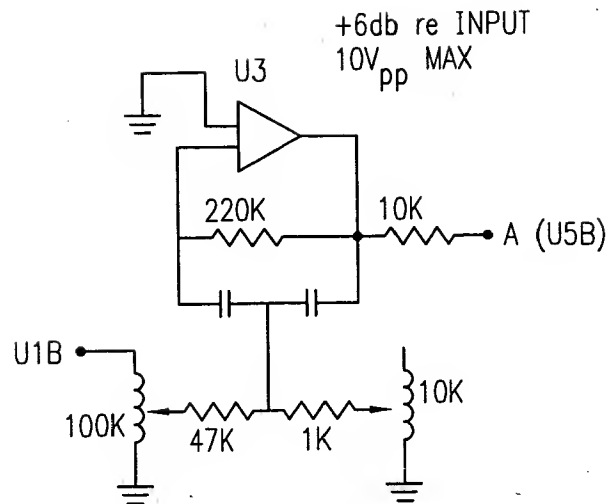


FIG. B2

FIG. B3



$0.0015 = 3.2 - 3.6k$  ( $2.5k \rightarrow 6.8k$ )  
 $0.0033 = 1.4 \rightarrow 1.7k$  ( $1.2k \rightarrow 3.3k$ )  
 $0.0047 \approx 900 - 1.2k$  ( $800 \rightarrow 2.2k$ )  
 $0.15 = 120$  ( $80 - 220$ )

LOWQ  $R|A| = 47k || 33k$   
 $RQ = 68k || 100k$

$V_{OUT} = 10V_{pp}$  MAX  
 (+6dB)

FIG. B4

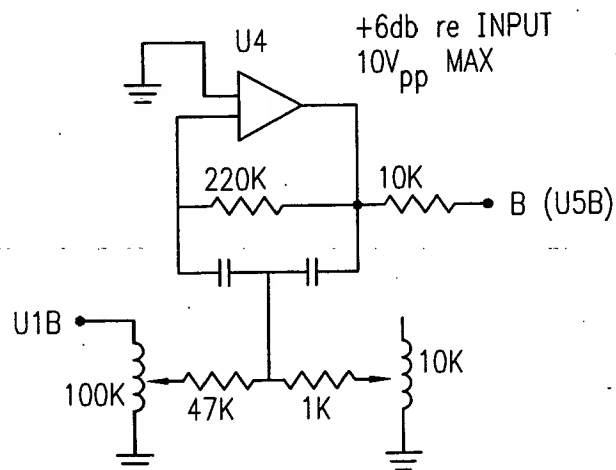
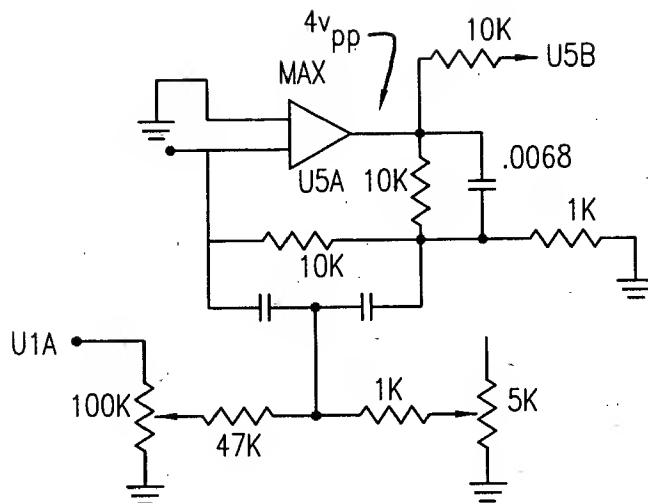


FIG. B5



0.033=270- $\rightarrow$ 1.4k

0.0068

700Hz opt  
@ 3/4 max  $W_0$

FIG. B6

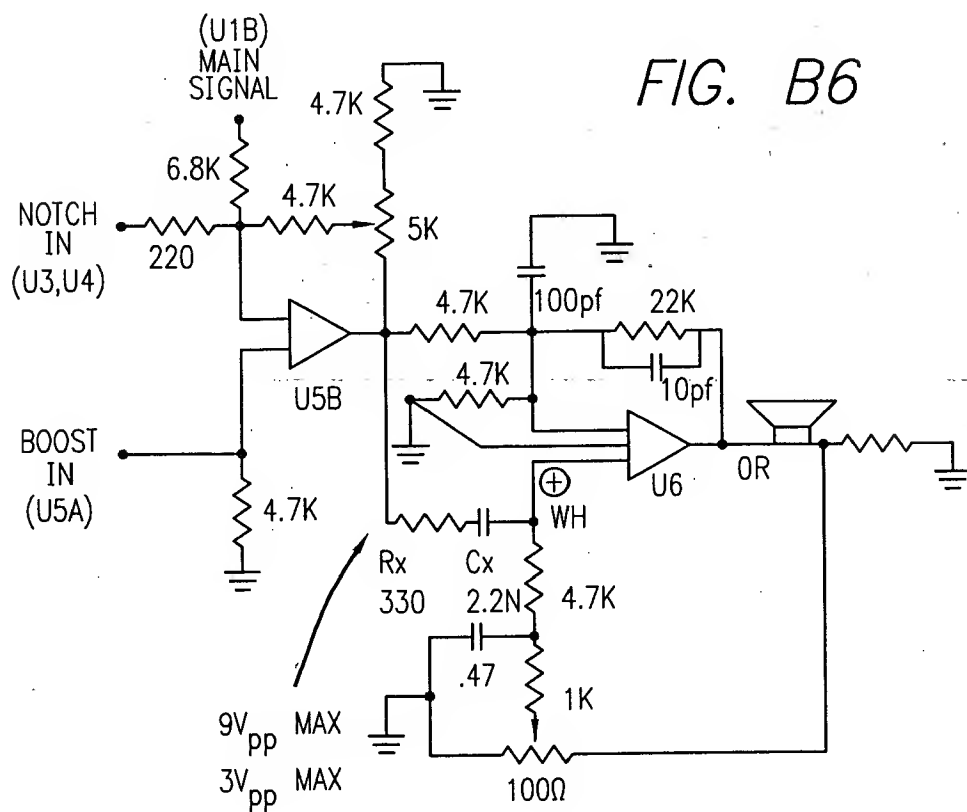


FIG. 5

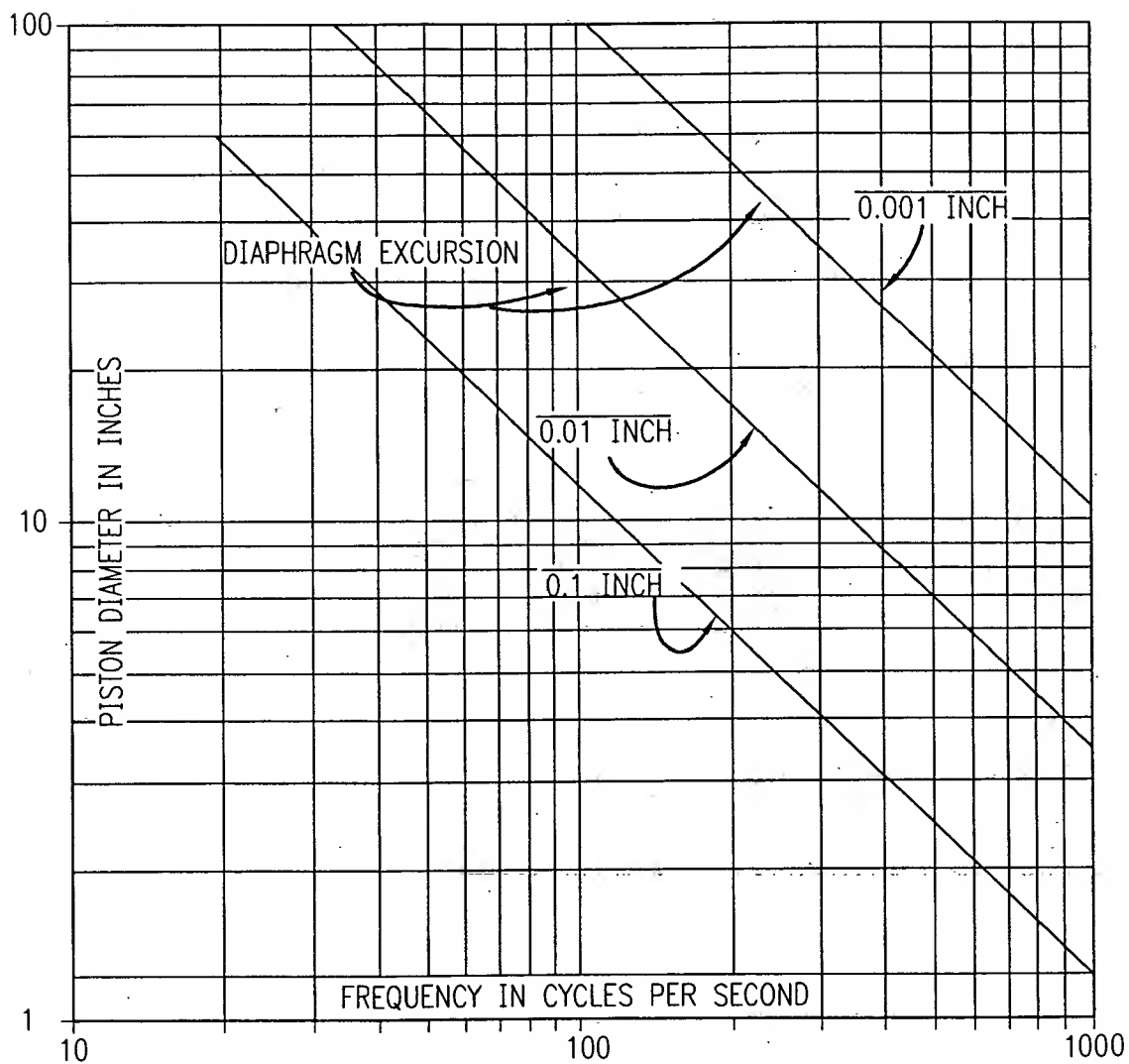
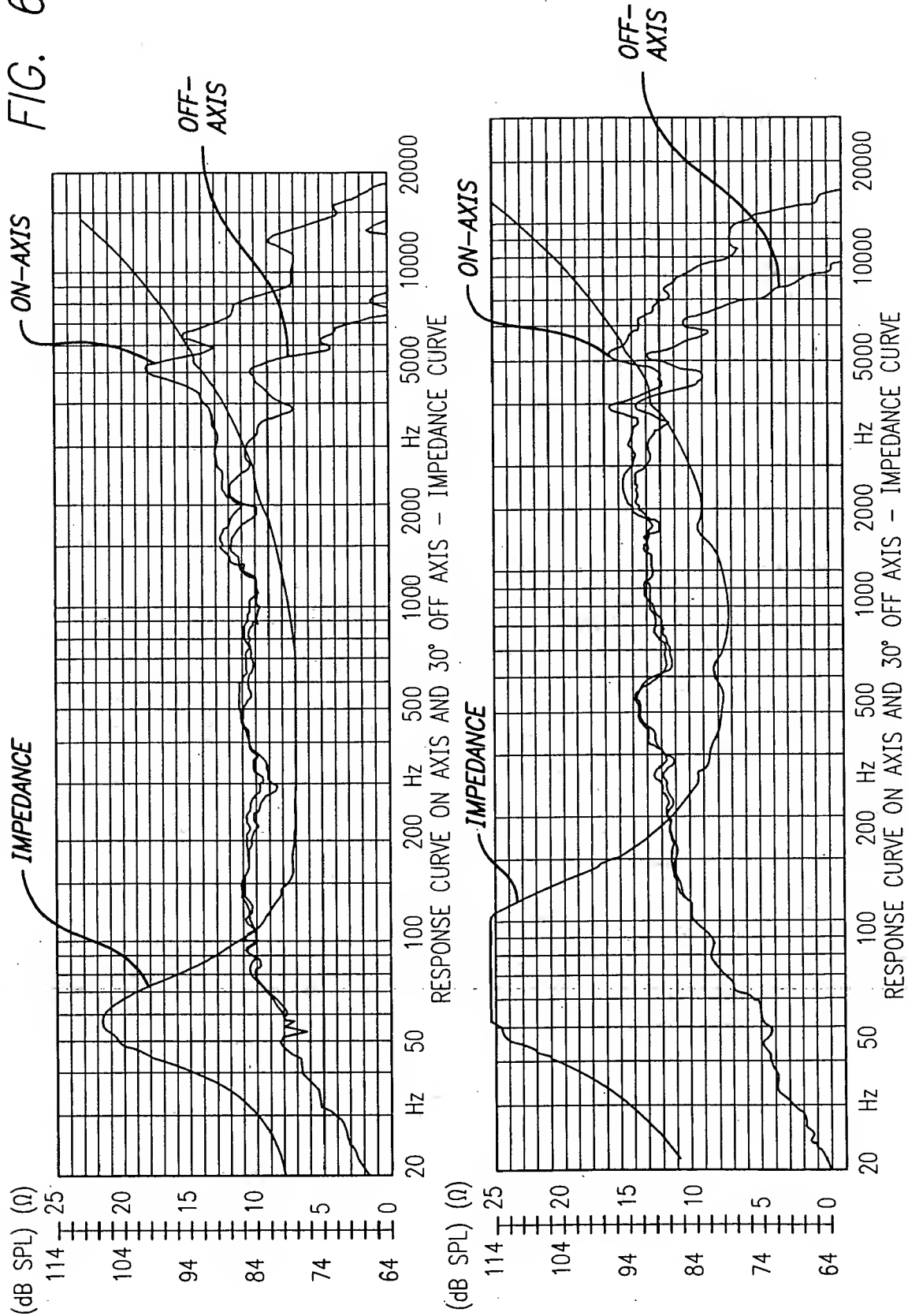


FIG. 6



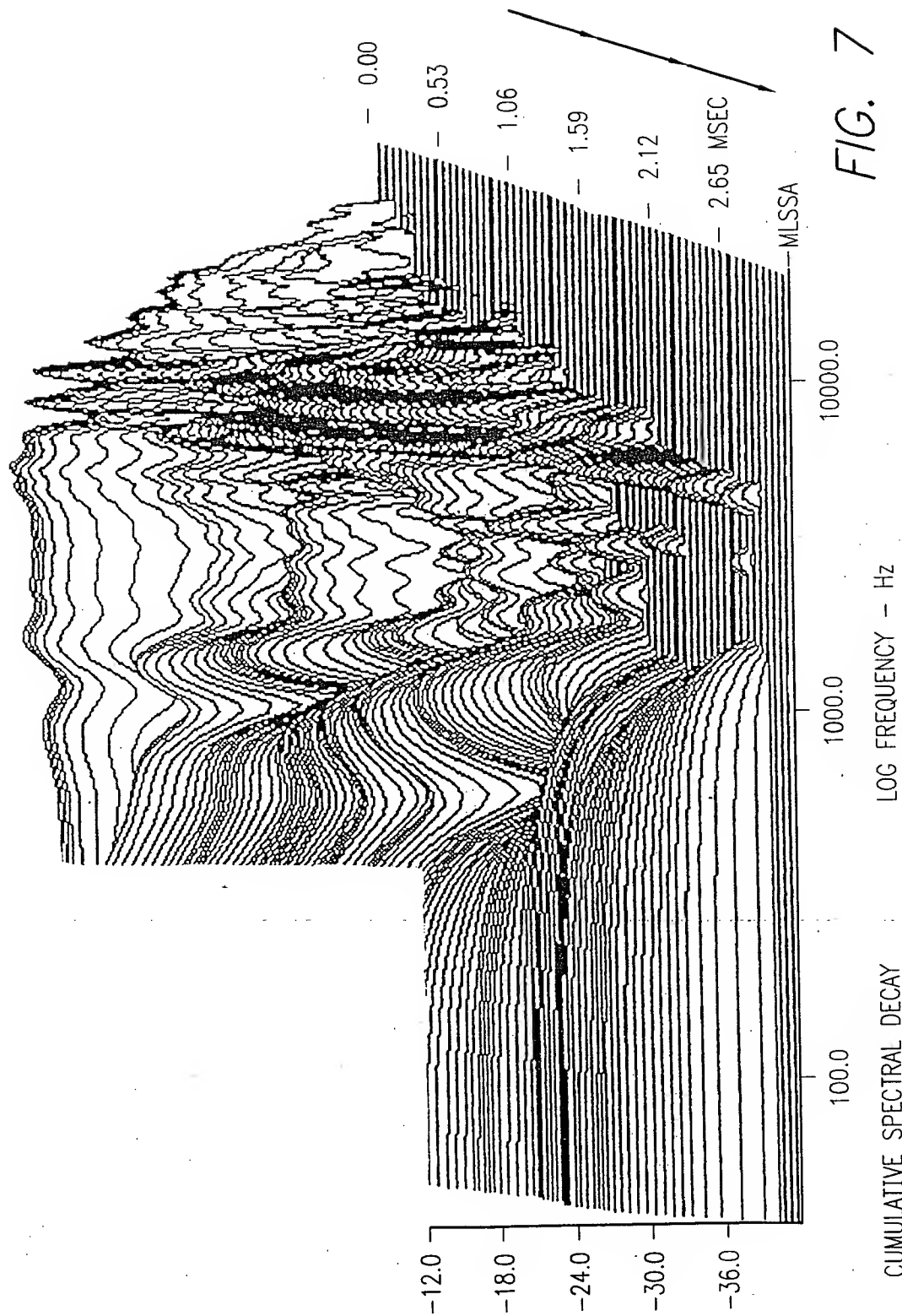




FIG. 8a

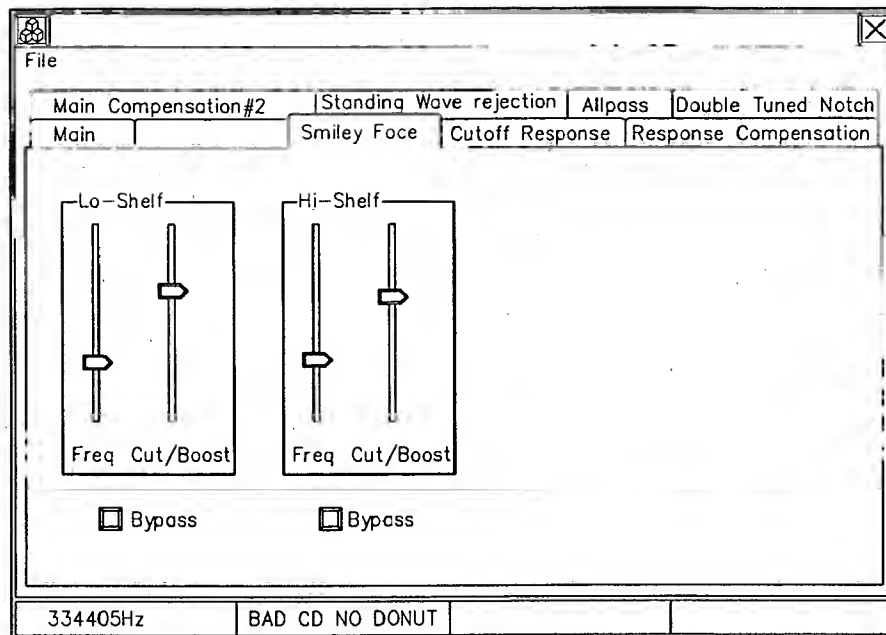


FIG. 8b

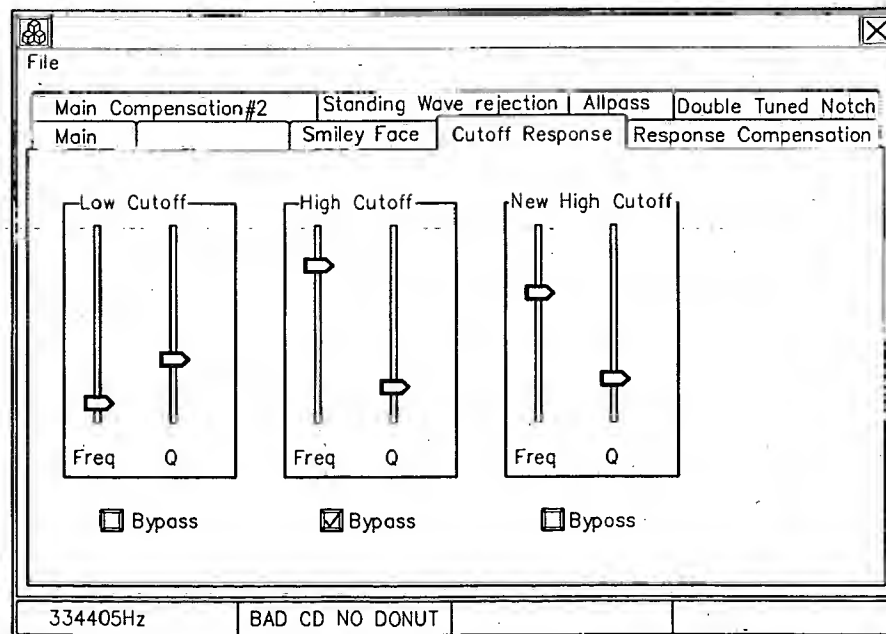


FIG. 8c

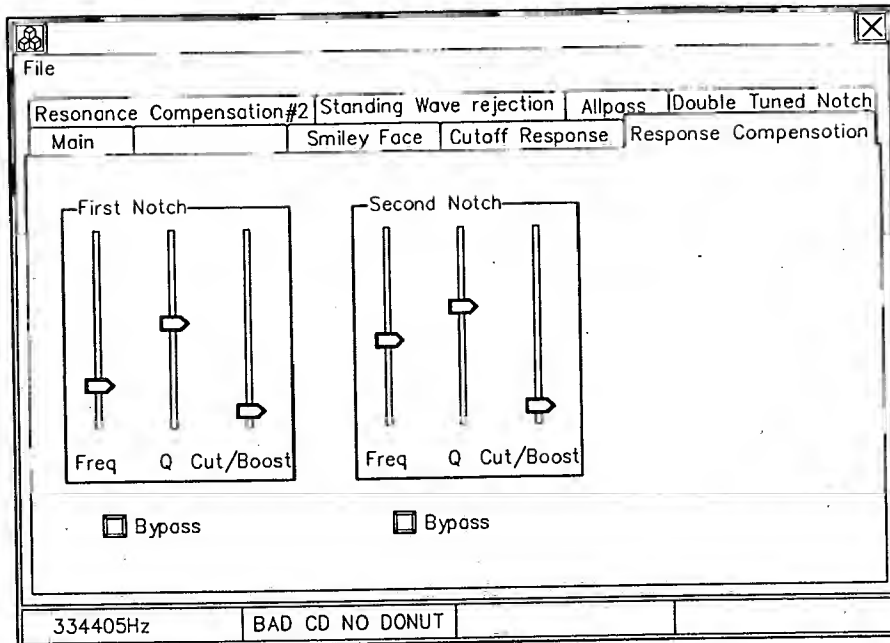


FIG. 8d

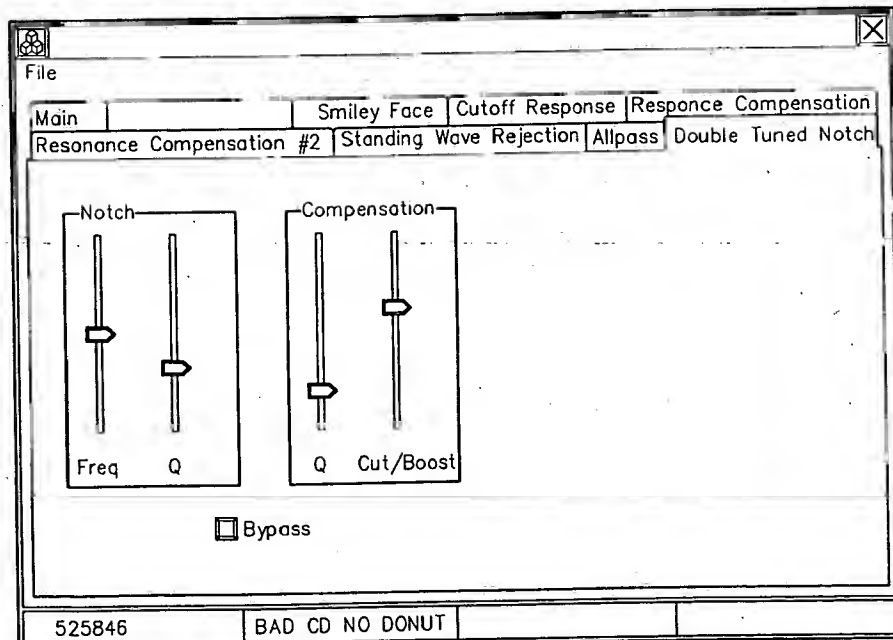


FIG. 8e

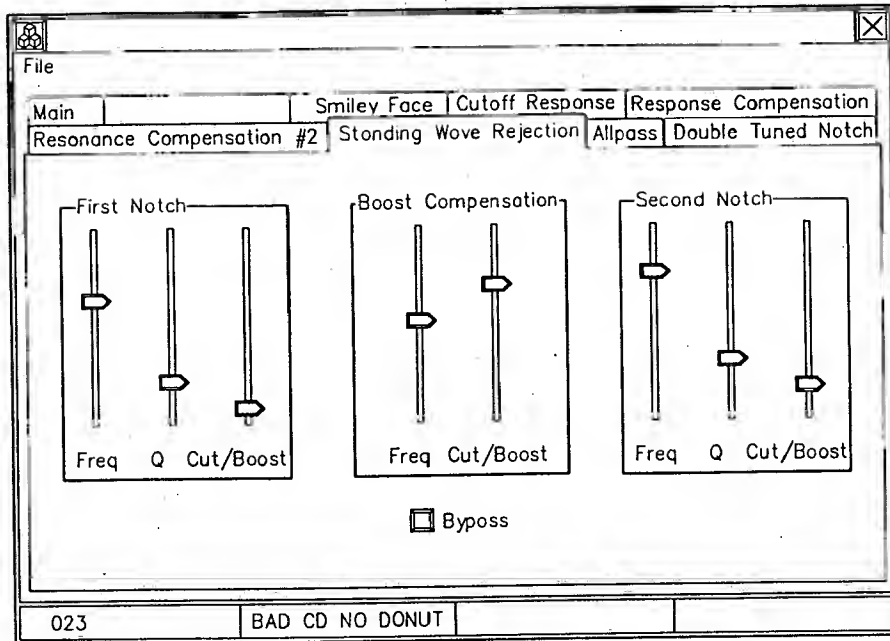


FIG. 8f

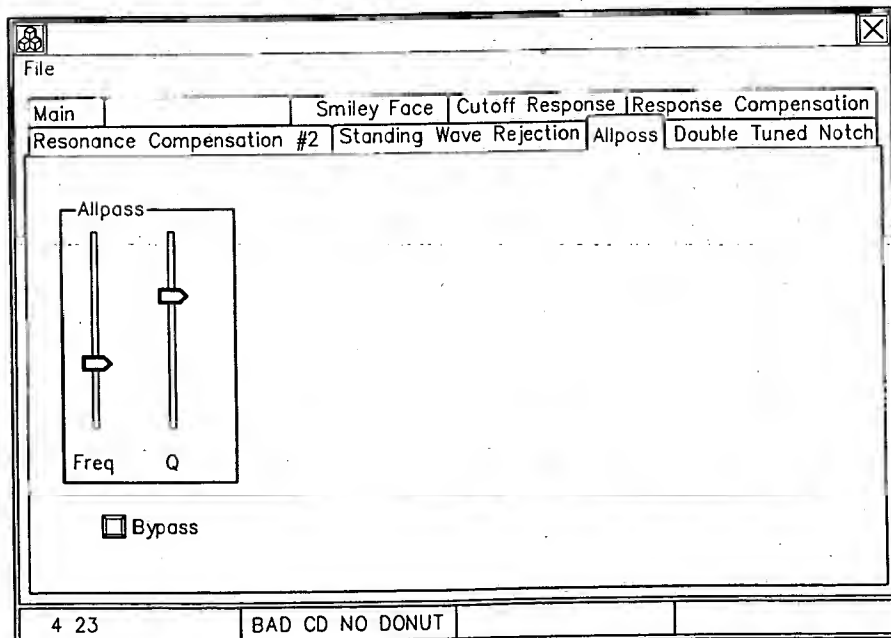


FIG. 9

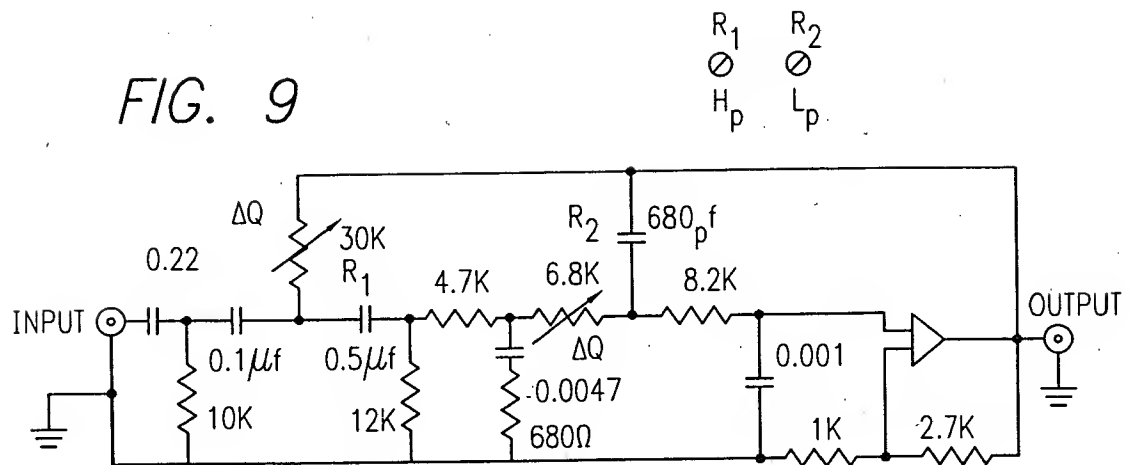


FIG. 10

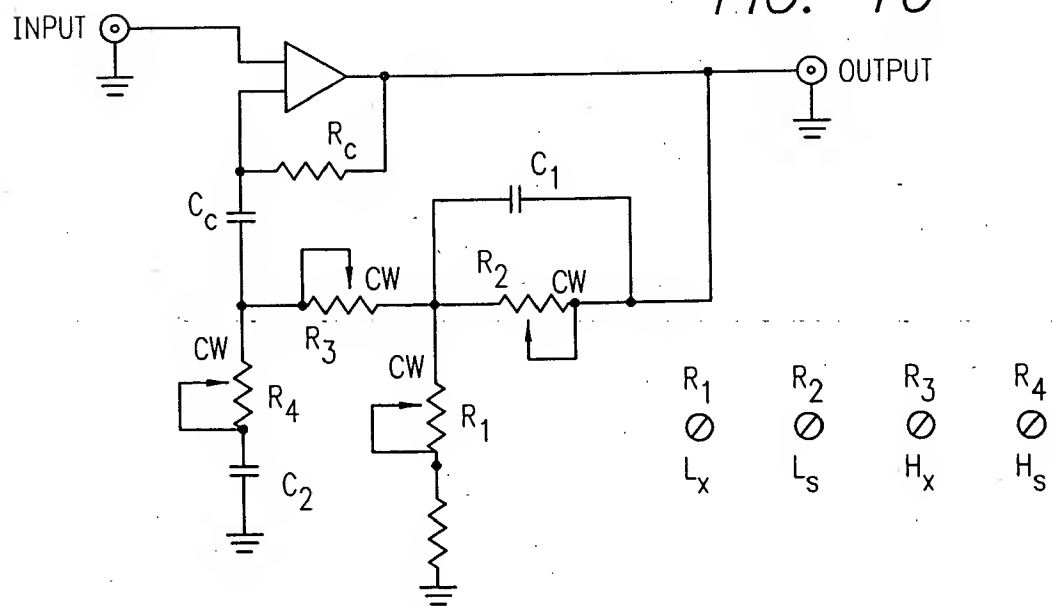


FIG. 11

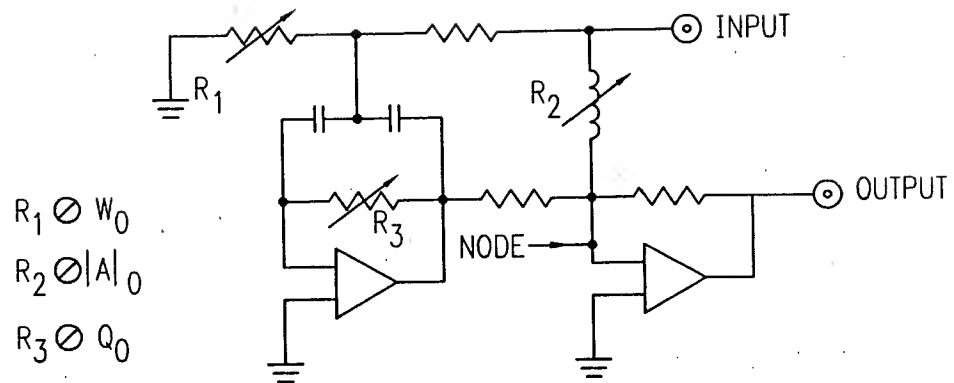
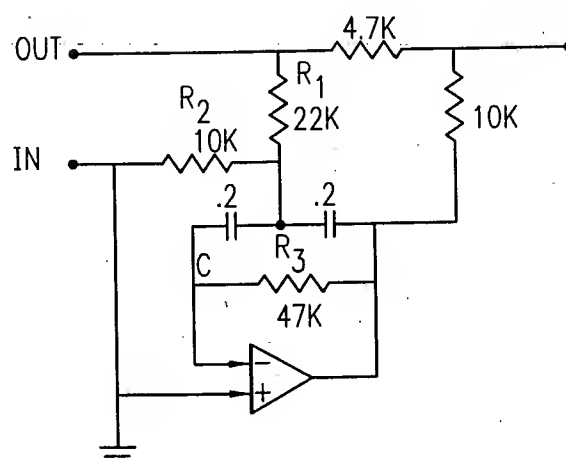


FIG. 12



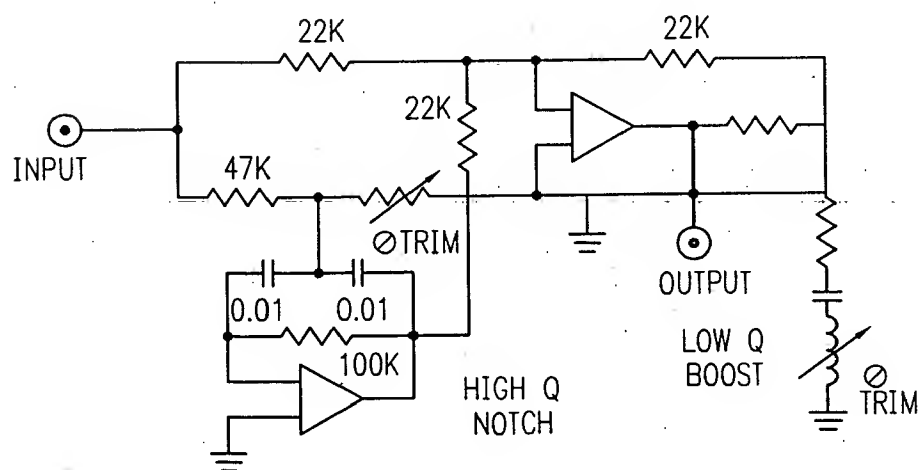
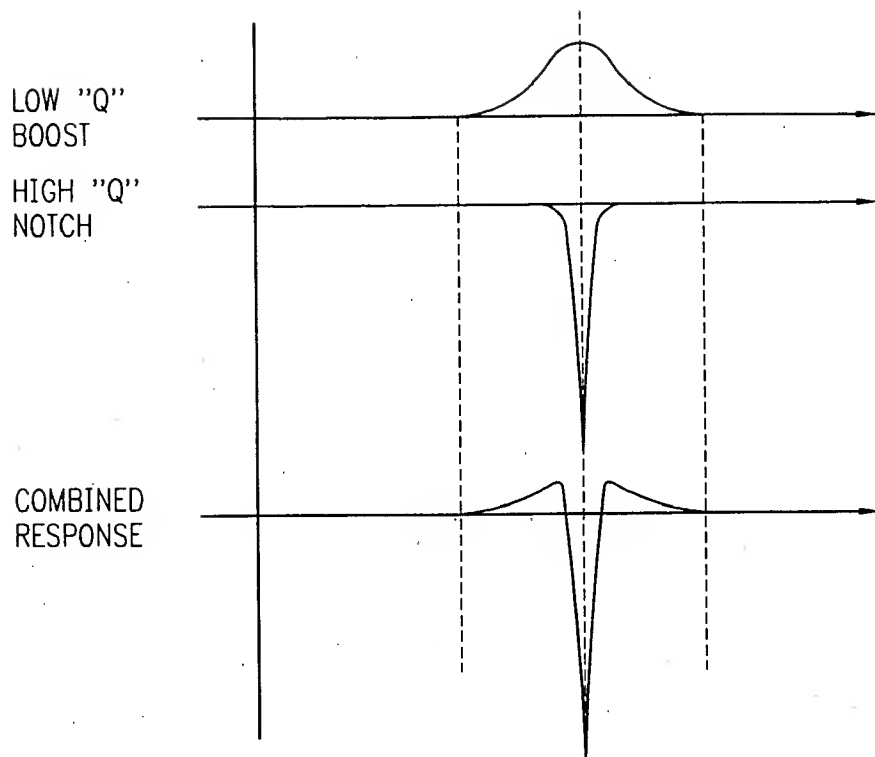


FIG. 13

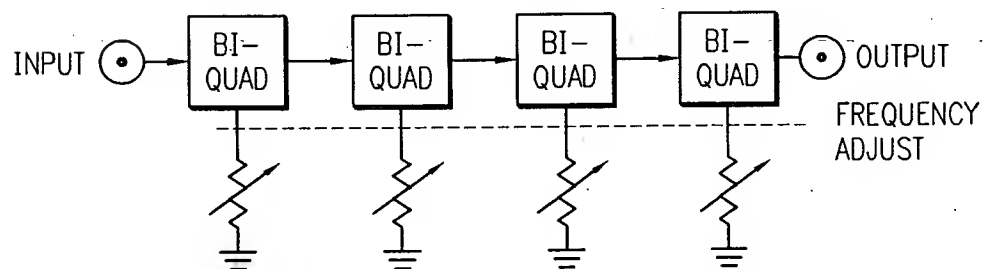
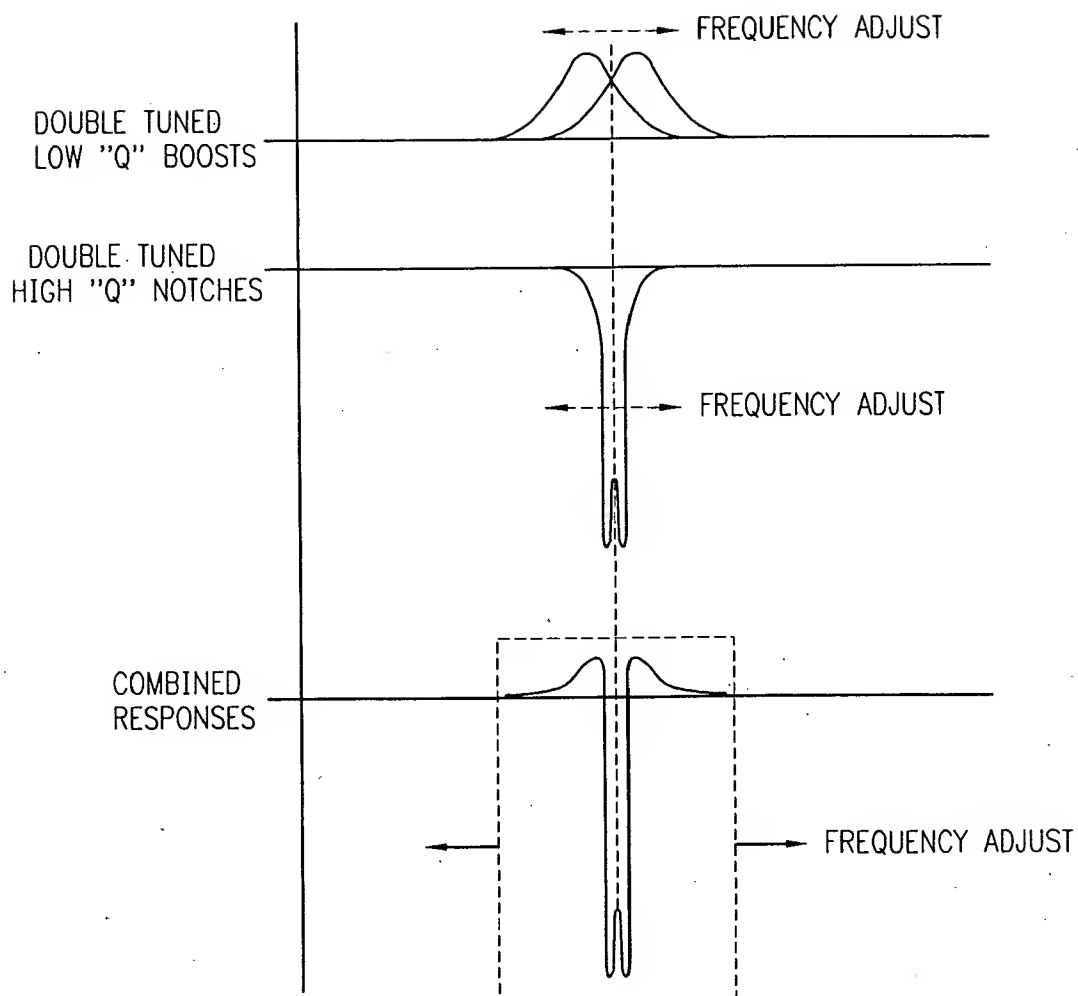


FIG. 14

FIG. 15

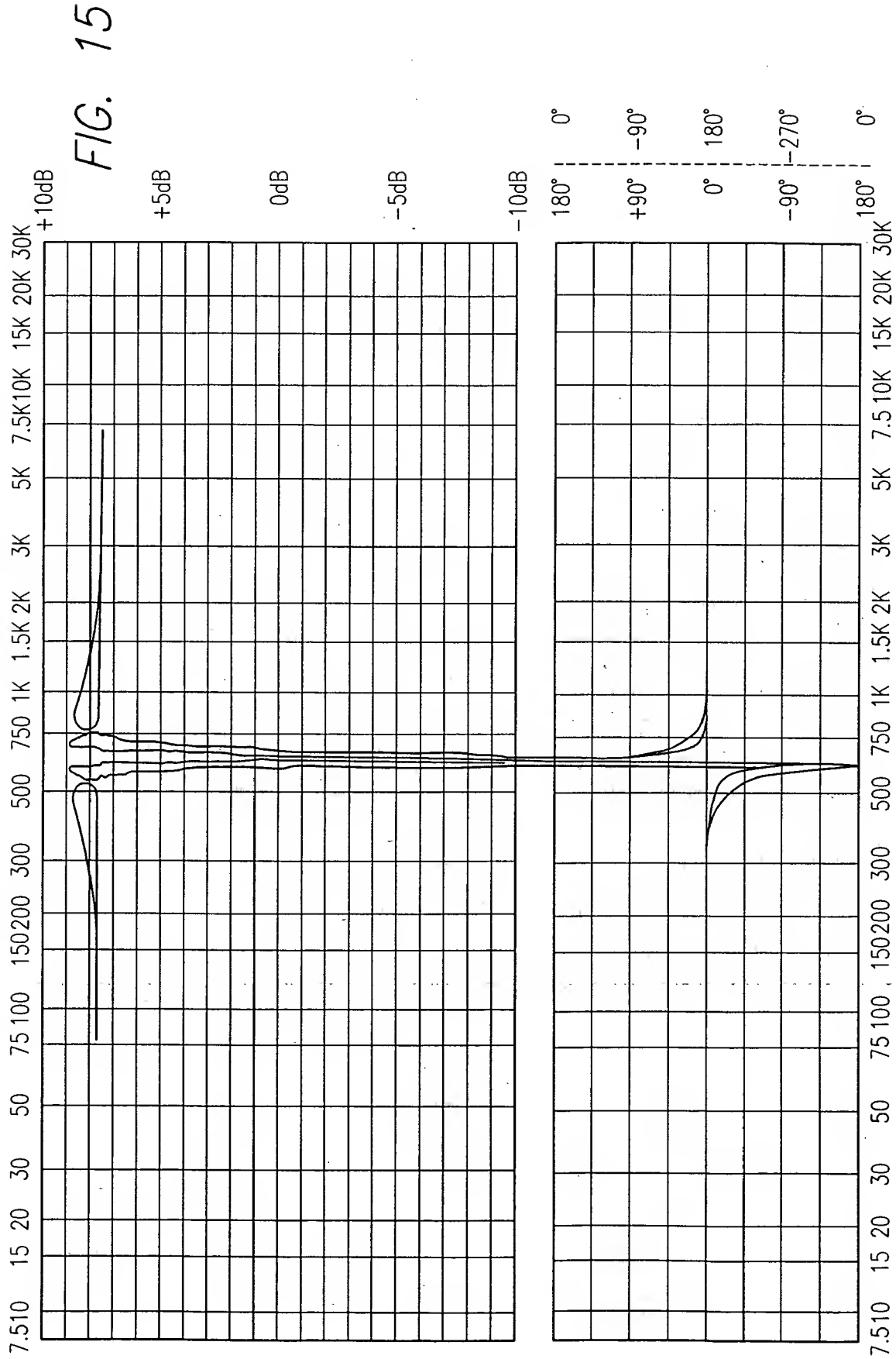




FIG. 16

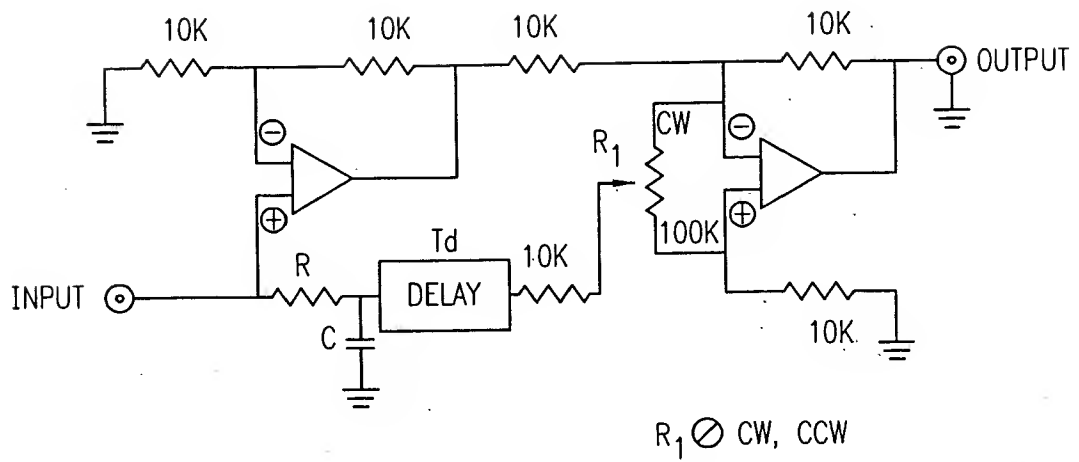
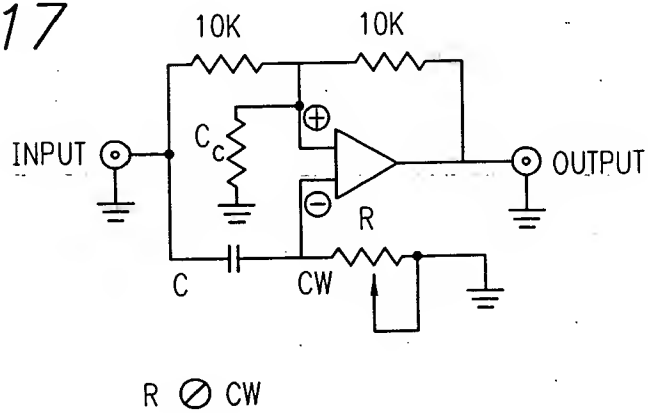


FIG. 17



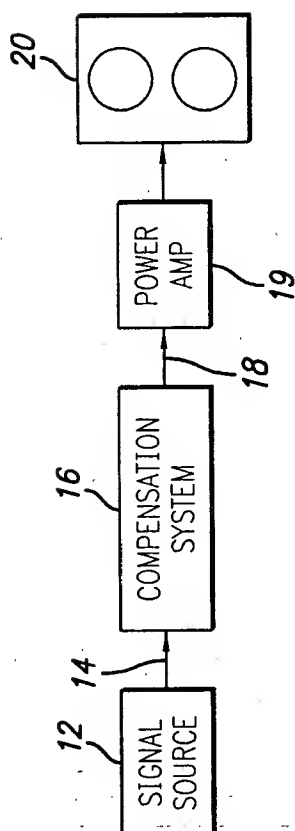


FIG. 1

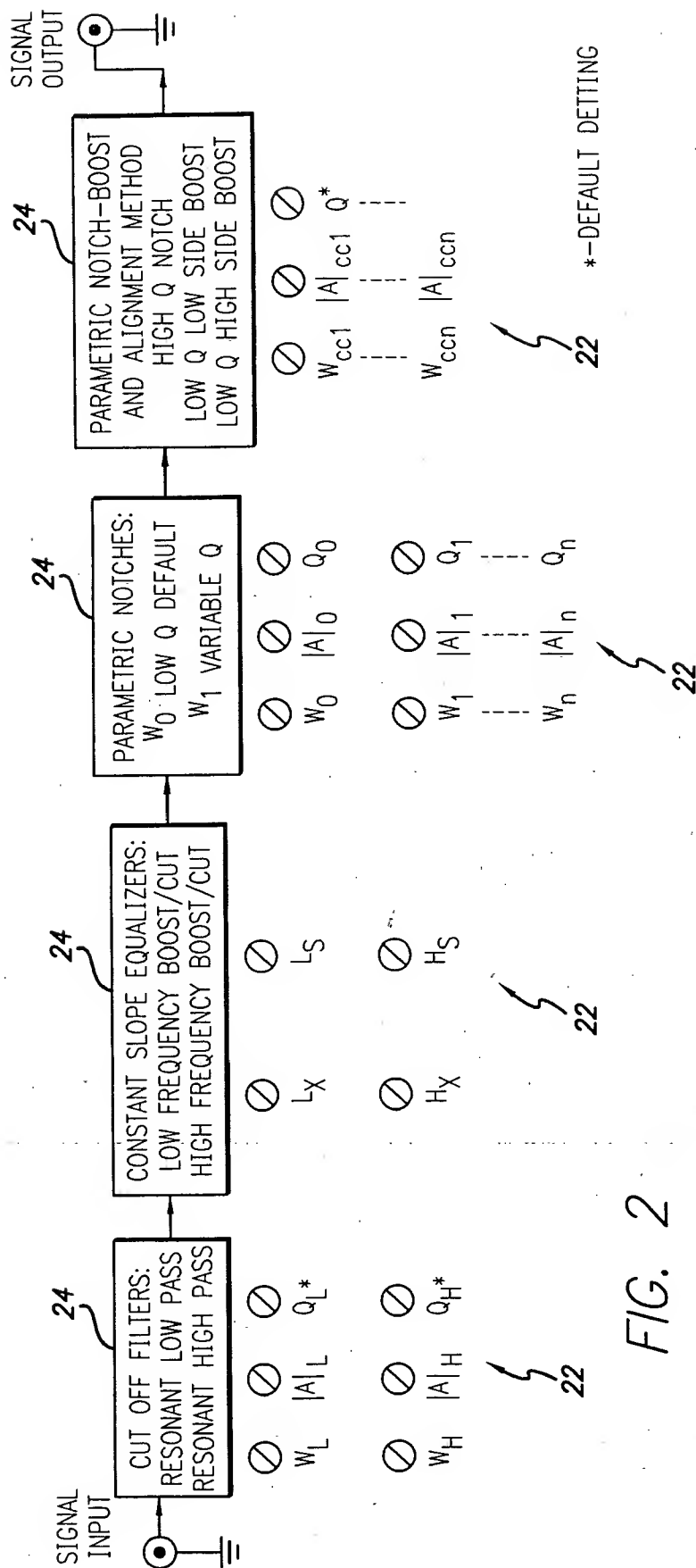


FIG. 2

FIG. 3a

ELECTRO MECHANICAL  
BEHAVIOR

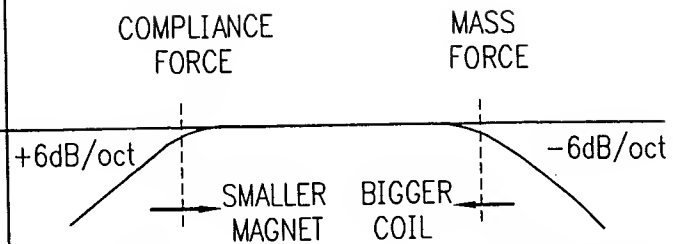


FIG. 3b

ACOUSTO MECHANICAL  
BEHAVIOR

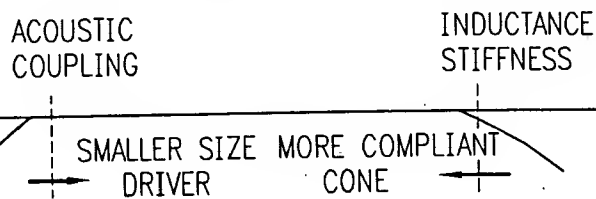


FIG. 3c

COUPLING  
BEHAVIOR

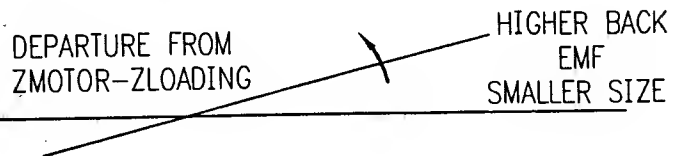


FIG. 3d

COMPLIANCE-AIR  
VOLUME RESONANCE  
AND  
MECHANICAL RESONANCE

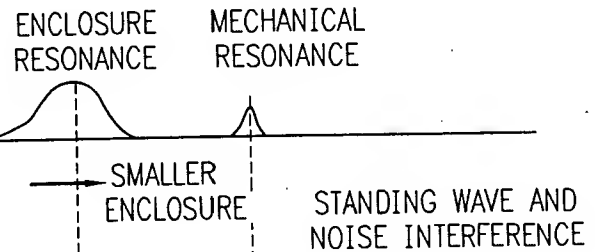


FIG. 3e

WAVE RELATED  
MECHANICAL  
BEHAVIOR

STANDING WAVE AND  
NOISE INTERFERENCE

FIG. 3f

OVERALL  
RESPONSE  
IN  
ENCLOSURE

OVERALL RESPONSE

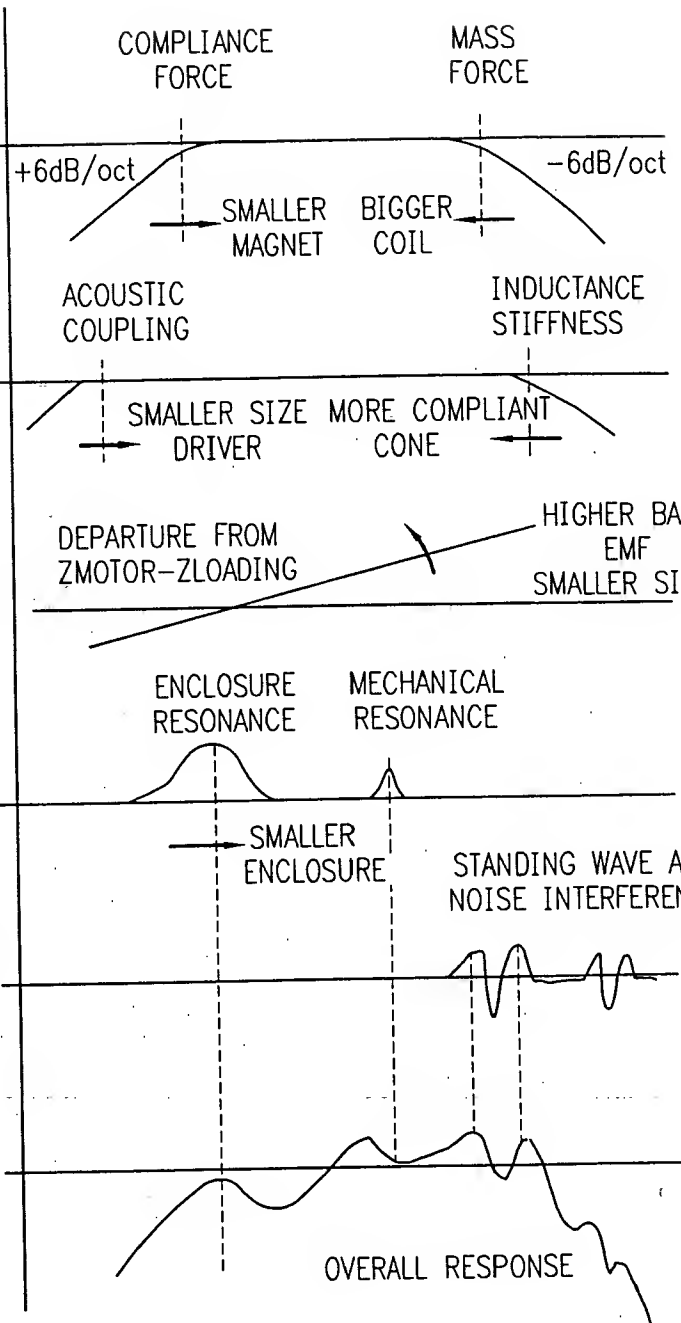


FIG. 4a

LOW-HIGH BOOST  
CROSSOVERS AND  
SHELF LIMITS

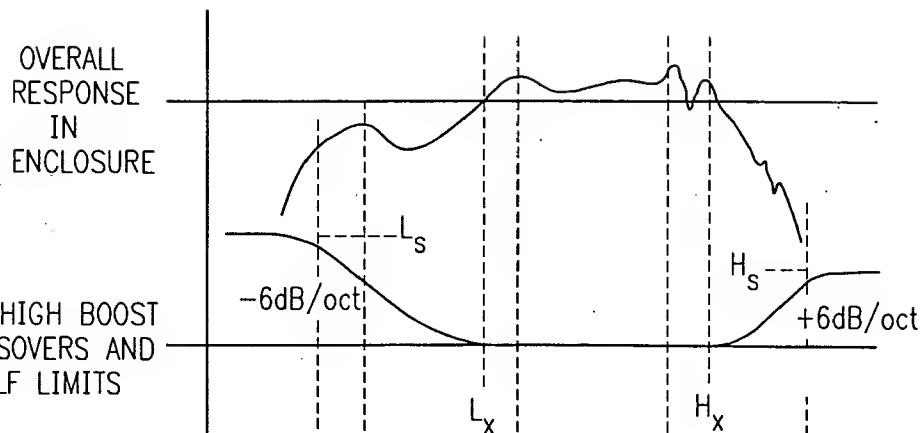


FIG. 4b

LOW-HIGH CUTOFFS  
AND PEAK COMPENSATION

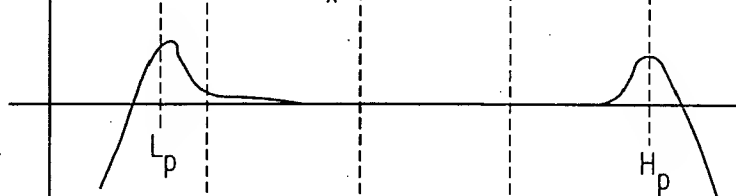


FIG. 4c

TILT  
EQ

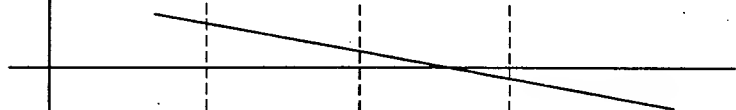


FIG. 4d

RESONANT  
NOTCHES

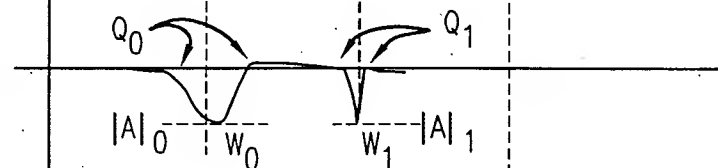


FIG. 4e

HIDDEN  
NOTCH

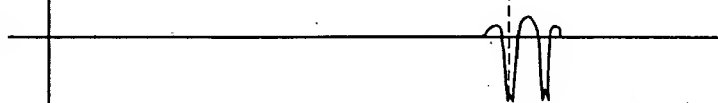


FIG. 4f

OVERALL  
CONJUGATE  
CORRECTION

